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Investigation of Turbulence Effect on the Free Space Optical Link for Ground-to-Train Communications

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Abstract— There is a growing demand for high mobility and ultrafast internet/data services which drives the motivation for free space optical (FSO) communications for high speed trains. Here we present an FSO link for the ground-to-train communications, which consists of optical transceivers positioned alongside the track and on the roof of the train. When the train moves at a high speed, the airwave induced turbulence degrades the FSO link performance. In this paper the effect of turbulence is experimentally investigated and compared with the case of no turbulence.

I. INTRODUCTION

FSO communication links are widely accepted as a complementary technology to the well established radio frequency (RF) wireless communications. FSO systems, similar to optical fibre systems, are better known for offering a huge unregulated license free spectrum, free from electromagnetic interference, low error rate transmission and excellent security [1-4]. Moreover, FSO systems are highly desirable in places such as hospitals, airplanes and campuses where there is restriction on the RF based systems [5]. However, the eye safety is an issue, which depends on the light source used and the operating wavelength [6]. The permitted optical power at a wavelength range of 780-850 nm is limited as the human eye is more sensitive at this wavelength, however at 1550 nm wavelength is relatively safe to operate and the transmit power can be increased up to 50 times without violating the eye-safety standard [7]. FSO systems can vary from the indoor short range ranging a few metres to the outdoor of a few kilometres link length. A bidirectional indoor optical wireless system operating at 1.25 Gb/s up to 4 metres is reported in [1] whereas outdoor line of sight FSO links at 2.5 Gb/s over several kilometres and at 10 Gb/s over 2 km are reported in [8] and [9], respectively. The key features of these systems are very narrow optical field of view and the eye safe limit.

The demand for access to a high speed internet on the move in application such as trains, buses and aircrafts is increasing exponentially. However the existing infrastructure based on the RF system cannot meet the demand because of licensing issue, bandwidth congestion and inter-cell interference [10]. As a result, though there is large potential for the expansion of business for service

providers, due to bottleneck imposed by existing infrastructure, the maximum data rate that can be provided per end user via 3G and HSPA (high speed packet access) mobile phone network is limited in the range of tens of kbit/s to a few Mbit/s in the best scenarios. To provide broadband internet services on the train, it is logical to directly connect the high-capacity optical fibre backbone network to moving trains via ground base stations using both the millimetre wave RF and FSO technologies. The latter of course offer much greater data rates and higher quality of service (QoS) compared to the former technology [3].

A typical ground-to-train FSO communications system has been proposed in [11, 12] illustrating the potential of this emerging technology. The papers have shown that for a real train system it is possible to achieve a bit error rate (BER) of 10^{-6} on a fine day up to communication distance of 22 m. However, the authors had not evaluated the performance of the proposed system in adverse weather conditions i.e. in the presence of the fog, snow and turbulence. When the train is moving at a very high speed, there is induced inhomogeneity in pressure around the train. This results in intensity scintillation leading to the random fluctuation of both the amplitude and the phase due to the fluctuations of the air refractive index [13, 14]. Thus the FSO link between train and ground base station could be disrupted or severely affected. In addition, a train moving at a few hundred kph could generate strong wind and turbulence that might affect the FSO link performance.

This paper reports the effect of turbulence on the BER performance of the proposed ground-to-train FSO link for a model train set and the results are compared with the case with no turbulence. The paper is organised as follows: the ground-to-train FSO communication links is described in Section II. A laboratory based experimental setup is explained in Section III and preliminary results are presented in Section IV. The concluding remarks are presented in Section V.

II. PROPOSED SYSTEM

The proposed ground-to-train communications system consists of a number of base stations (BSs) located along

the track and transceivers positioned on the roof of the train coaches as shown in Fig. 1. In this figure the communications link for one coach is shown that provides continuous full duplex communication link between the train and the BS which could be connected to the optical fibre backbone network. As long as the train is within the coverage of a BS, for example BS1, then the BS is switched on. Other BSs remains idle during this time. As the train approaches the coverage region of the BS2, a handover takes place between the BS1 and BS2. In this way, communications between the train and the BS is maintained at all times.

Fig. 2 depicts the layout of the proposed model showing the position of the BS at a horizontal distance d_1 from the track. The BS would be tilted at an angle α towards the incoming train where the receiver positioned on top of the train coach would collect the transmitted beam. The effective coverage length along the track is L

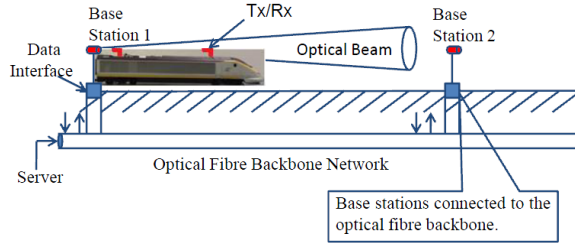


Fig. 1 Proposed FSO train system.

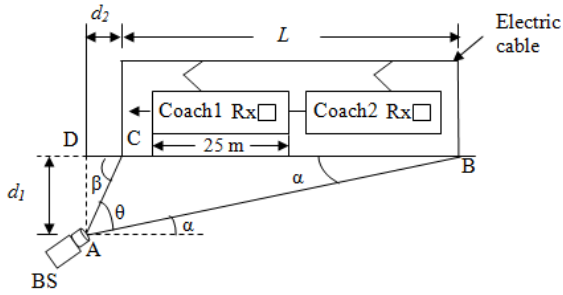


Fig. 2 Layout of the proposed model.

and d_2 is the position of the BS from point C.

If α is coverage angle at the longest point B, β is the coverage angle at the shortest point C and θ is the field-of-view (FOV) of the transmitter, then from simple geometry,

Using (1), (2) and (3), the FOV of the transmitter at the BS can be derived as follows:

Equation (4) gives the estimation of the FOV of the transmitter. In order to provide the coverage for at least two train coaches, $L = 60$ m, $d_1 = 2$ m and $d_2 = 5$ m (typical values) yields the value of θ to be 20° .

III. EXPERIMENTAL SYSTEM DESIGN

The block diagram of the experimental setup of the FSO communication system composed of a transmitter, an atmospheric channel (simulation chamber) and a receiver is shown in Fig. 3.

A. Transmitter

The transmitter consists of a light emitting diode (LED) driver circuit, an infrared (IR) LED, an optical lens and a data source. The LED bias and modulation currents are 40 mA and 55 mA, respectively. The LED is modulated with the pseudo-random non-return-to-zero (NRZ) on-off-keying (OOK) signal generated from an arbitrary waveform generator. The optical biconvex lens collimates the radiated beam from the LED to provide the effective full-angle FOV of 5.20° , thus ensuring the optical receiver mounted on the train is well illuminated as well as ensure full tracking. The driver board with the LED is shown in

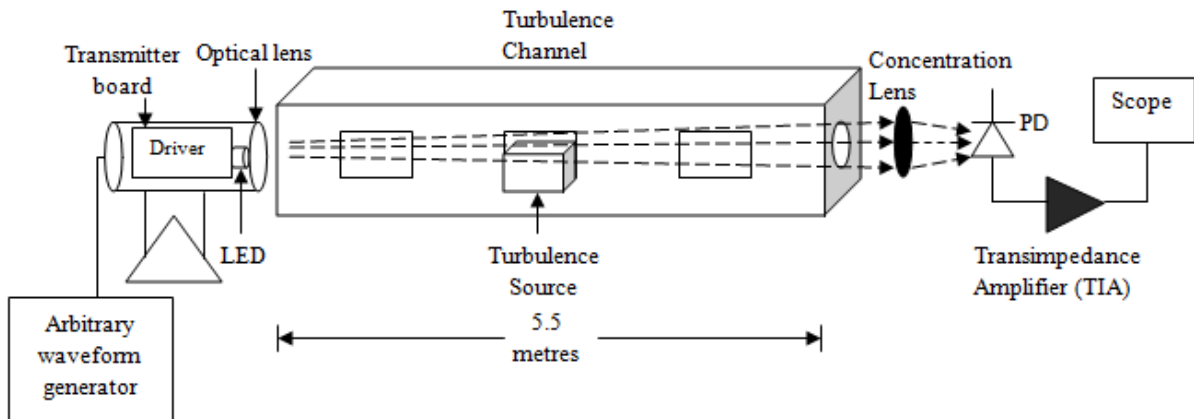


Fig. 3 Block diagram of experimental setup of the FSO link.

Fig. 4 which is fabricated into a single transmission module along with the optical lens (see Fig. 3).

B. Atmospheric Channel

In order to simulate the effect of atmospheric turbulence, a purpose built FSO laboratory atmospheric chamber of glass $550 \times 30 \times 30 \text{ cm}^3$ dimensions is used (see Fig. 3). The chamber is made up of a number of compartments, with an air vent to control the air flow and temperature. In this experimental setup, turbulence is created by injecting hot air inside the chamber via one of three inlets located at each end and at the centre of the chamber. The hot air is pumped using the heater fans at a speed of 4 m/s. The strength of the turbulence can be changed by either increasing the hot air flow or by changing the temperature difference along the chamber. The chamber is kept at the normal atmospheric pressure of $\sim 1010\text{-}1016 \text{ mbar}$ and the average temperature of chamber is just kept above the room temperature. The optical beam propagating along the chamber experiences different atmospheric turbulence before being collected at the photodetector.

Here we are mainly focusing on the weak turbulence regime, which is best described by the log-normal model as given by [15] :

$$y(I) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(\ln(I/I_0) + \sigma^2/2)^2}{2\sigma^2}\right)$$

where $y(I)$ is the probability density function (pdf), I and I_0 are the average optical irradiance with and without turbulence, respectively and σ^2 is the log irradiance variance and is considered as a Rytov parameter, which indicates the strength of the turbulence.

The normalised Rytov variance for this system is calculated using the expression as given by [16] :

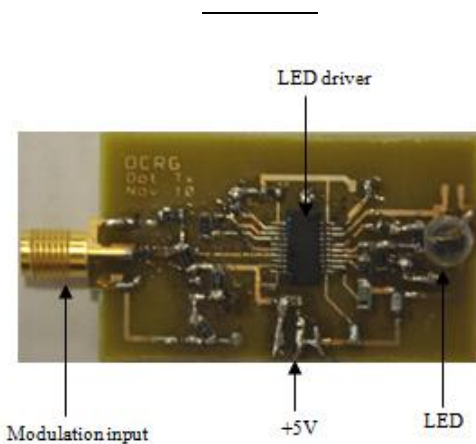


Fig. 4 Transmitter driver circuit

where the angle brackets $\langle \cdot \rangle$ denote a long-time average.

C. Receiver

The receiver comprises of an optical concentrator, a PIN photodiode with an active area of 7 mm^2 and a transimpedance amplifier (TIA). The optical lens with a focal length 100 mm and a diameter of 40 mm collects the optical transmitted beam and focuses it onto the photodiode. The photodiode is coated with a daylight filter with a band-pass wavelength range of 800 - 1100 nm which is used to reject the ambient light interference in the visible band (400 - 700 nm). The TIA has a theoretical bandwidth of 240 MHz with an optical sensitivity of -36 dBm at a data rate of 20 Mbps. Fig. 5 show the optical system for the receiver and the prototype circuit. The output of the TIA is connected to the oscilloscope for recording the temporal waveform.

The use of an optical concentrator improves the optical gain of the system and the effective collection area of the receiver. The receiver effective area A_{in} with the concentration lens is given by [17]:

$$A_{in} = A_{det} \left(\frac{D}{d} \right)^2 \quad (7)$$

where A_{det} is the collection area of the photodetector (7 mm^2), θ_a is the FOV which is 8.56° and n is the refractive index of the optical concentrator at the receiver (see Table I). Using (7), the effective area of the receiver can be

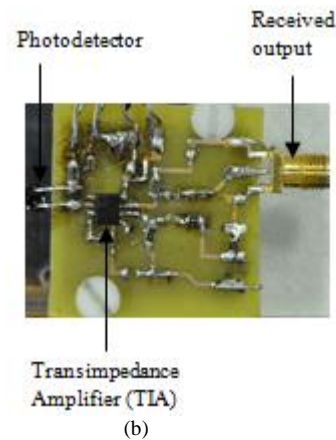
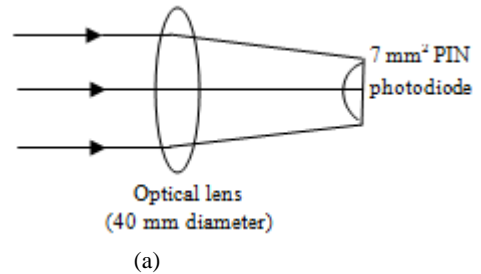


Fig. 5 (a) Receiver optics design and (b) the prototype receiver circuit

TABLE I
EXPERIMENTAL SETUP PARAMETERS

Parameter		Value
Data source	Data rate	20 Mbps
	PRBS length	$2^{10}-1$
	Modulation Format	NRZ OOK
	Optical transmit power	5 mW
LED (HIRL5015)	Peak wavelength	865 nm
	Radiant intensity	80 mW/sr @ 100 mA
	Half angle (FOV)	$\pm 30^\circ$
	Rise time	30 ns
	Fall time	15 ns
Optical lens	Diameter	20 mm
	Focal length	30 mm
PIN photodiode (SFH205F)	Spectral range of sensitivity	800-1100 nm
	Wavelength of maximum sensitivity	950 nm
	Active area	7 mm ²
	Half angle (FOV)	$\pm 60^\circ$
	Responsivity	0.59 A/W
	Rise and fall time	20 ns
	Forward voltage	1.3V
Concentration lens	Diameter	40 mm
	Focal length	100 mm
	Refractive index	1.5
Trans-impedance amplifier (AD8015)	Bandwidth (3 dB)	240 MHz
	Rise and fall time	1.5 ns
	Supply voltage	5 V
	Receiver sensitivity	-36 dBm @ 20 Mbps

calculated to be 7 cm².

In order to analyse the performance of the FSO system under different atmospheric conditions, the Q -factor which represents the signal-to-noise ratio (SNR) is calculated using [18]:

$$(8)$$

where $\mu_{1,0}$ is the mean values and $\sigma_{1,0}$ is the standard deviations.

The BER of the optical communications system can be predicted using the Q -factor and the complementary error function $\text{erfc}(x)$ given as:

$$(9)$$

IV. RESULTS AND DISCUSSION

In order to evaluate the performance of the communication system, a pseudo-random binary sequence (PRBS) of $2^{10}-1$ length is used to intensity modulated the light source prior to transmission over the chamber. The important parameters of the FSO system are summarized in Table I. The experiment is carried out with and without turbulence.

Fig. 6 illustrates the eye diagrams of the received signals at a data rate of 20 Mbps with and without the turbulence. The figure clearly demonstrates that the eye-width decreases by approximately 40 % for a Rytov variance of 0.016 compared to the case with no turbulence.

Fig. 7 demonstrates the Q -factor against the Rytov variance of 0 to 0.016. The Q -factor decreases from 7.45

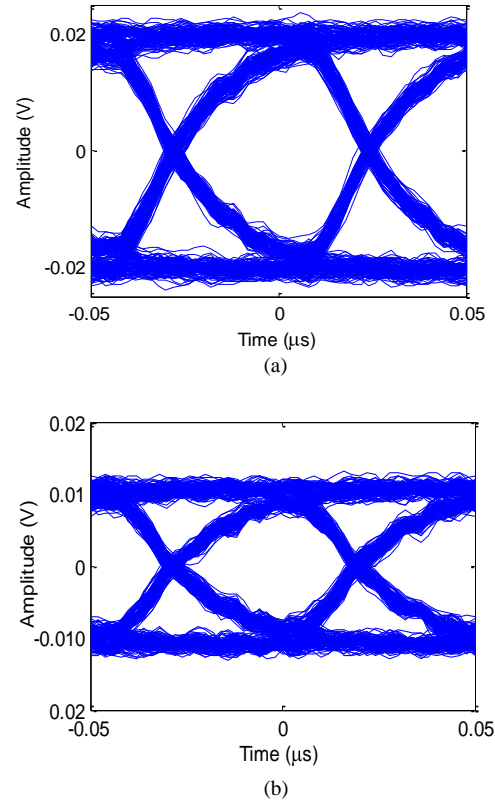


Fig. 6 Eye diagrams for received OOK-NRZ signal at 20 Mbps (a) without turbulence and (b) with Rytov variance of 0.016.

in the absence of turbulence to 5.52 for a Rytov variance of 0.016. The effect of turbulence is maximum (corresponding to the least Q -factor) when the turbulence source is at a transmitter end since the transmitted beam experiences high degree of bending when the hot air is pumped through the compartment near the transmitter. However, the effect of the turbulence is the minimum when the turbulence source is near the receiver. Notice that in order to avoid the need for tracking (it is rather challenging to incorporate a tracking system at a very high speed), a wide beam of ~ 50 cm diameter at the receiver as well as an optical concentrator are employed at the receiver. As a result, the effect of the turbulence is not

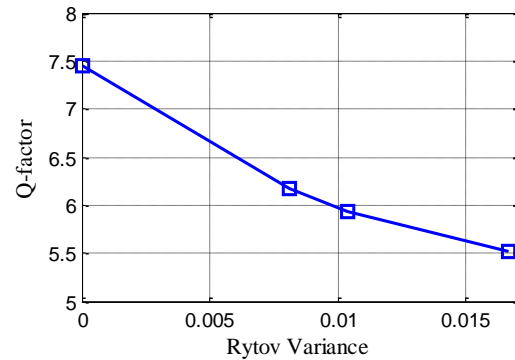


Fig. 7 Measured Q values against a range of Rytov variance for 20 Mbps OOK -NRZ signal.

that significant for the Q -factor of 5.52 corresponding to the BER of 10^{-8} at the maximum measured turbulence level (note that scintillation noise can be reduced by aperture averaging [19]). The BER of 10^{-8} is still lower than the minimum acceptable level of 10^{-6} .

V. CONCLUSIONS

In this paper, the performance of a FSO ground-to-train communications system in the presence of weak turbulence has been studied. An experimental investigation was carried out in the laboratory based turbulence chamber. Despite the effect of turbulence, the results obtained suggest that the performance of the system is not degraded severely and the BER of the system for the worst case (i.e., for maximum turbulence) is less than 10^{-8} . This is due to the relatively wide beam profile of the FSO link compared to the long-haul system. The result showed that the proposed ground-to-train communications link has high degree of tolerance to the effect of turbulence.

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